Positron Plasma in the Laboratory

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We have developed a method to accumulate and store positrons, from a ^{22}Na radioactive source, in an electrostatic trap using a tungsten moderator and inelastic collisions with nitrogen molecules. The resulting positron gas is found to cool to room temperature, and to fulfill the criteria for a single-component, positron plasma. The cooling and confinement processes and the potential applications of this many-positron system are discussed.

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In the past two decades, study of the behavior of positrons in the laboratory has provided new insights into atomic and molecular physics and many aspects of condensed matter and surface physics.[1] A natural extension of this research is to learn how to accumulate and store sufficient numbers of positrons so that they behave as a collective, many-body system.[2-4] In this Letter, we describe an experiment which has achieved the trapping of 3.3×10^5 positrons with a characteristic confinement time of 60 s in a volume of 12 cm^3. Inelastic scattering with a background gas of N_2 molecules is used to cool the positrons to nearly room temperature in about 3 s, and the present experiments can provide a measure of these scattering processes.

The resulting positron gas fulfills the requirements on density n and temperature T for it to act collectively as a classical, single-component positron plasma. In particular, at room temperature and the highest positron density achieved, the Debye screening length λ_D which is the distance over which the positrons screen electric fields in the plasma, is smaller than for the size of the charge cloud. The other criteria for classical plasma behavior are easily fulfilled; i.e., $n\lambda_D^3 \gg 1$, and the plasma frequency is large compared with the positron–neutral-molecule collision rate.

We envision that, with the addition of electrons, the trapping scheme described here will be useful in studying the unique aspects of electron-positron plasmas.[2,5] These techniques are also likely to be useful in accumulating large numbers of positrons for a range of other applications, including antihydrogen formation, the study of inelastic processes involving atoms and molecules,[6] use as a low-emittance source for accelerators,[4] and use as a diagnostic of transport in fusion plasmas.[7]

The electrostatic trapping scheme, which has been described elsewhere,[3,4,7] is shown schematically in Fig. 1. The design of the final stage of the confinement device is modeled after that developed to confine single-component electron plasmas.[8] In order to trap large numbers of positrons, we require an efficient method of filling the trap. We use a single-crystal tungsten moderator[9] to convert positrons from an 86-mCi ^{22}Na radioactive source (with energies of several hundred keV) to slow positrons with energies $\sim$2 eV. The efficiency of the moderator is approximately 6×10^{-4}.[9] The positrons are then accelerated to 40 eV and guided by an axial magnetic field to the series of potentials shown in Fig. 1.

Using differential pumping techniques and a suitably designed electrode structure, three regions (labeled I to III in Fig. 1) are created, each having an axial magnetic field and a different electrical potential and N_2 gas pressure. The pressure is adjusted so that inelastic ionization and/or electronic excitation of the N_2 in the highest pressure region, which operates at 1×10^{-3} Torr (region I), traps the positrons between $z=0$ and $z\simeq165$ cm in one pass through the trap. In order to prevent rapid diffusion across the magnetic field, the trap is designed so that the positrons quickly make subsequent inelastic collisions to be trapped in the lower-pressure regions—first

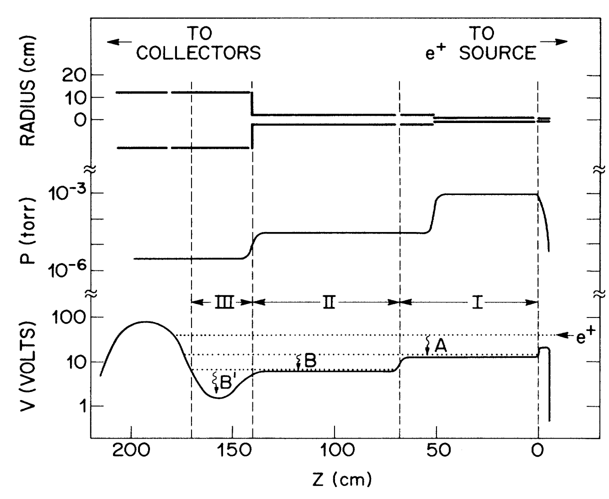

FIG. 1. A schematic diagram of the three-stage positron trap, including the electrode structure, nitrogen gas pressure, and the electrostatic potential profile. There is an axial magnetic field in the z direction whose magnitude is 860 G in confinement region III. The positrons lose energy by electronic excitation and/or ionization of the N_2 (labeled A) or by vibrational excitation of the N_2 (B and B′).

in regions II and III, and then finally in region III alone. These latter stages are designed to operate at energies below the threshold for positronium formation (i.e., 8.8 eV in N_2), using vibrational excitation of the N_2 as an inelastic scattering mechanism. The intrinsic efficiency of the trapping scheme is limited by positronium formation in region I. We have measured the magnitude of the loss process to be 75% by measuring the number of positrons with energies below 8.8 eV surviving after one pass through the trap.

After filling and storage for given lengths of time, the trapped positrons are detected by measuring the 511-keV annihilation radiation produced when they are dumped on an arrangement of metal collector electrodes. The resulting annihilation radiation signal is detected using a NaI crystal and pulse-counting electronics. The efficiency of the detection system was determined by placing a source of known strength at the position of the collector electrodes.

The time dependence of the total number of positrons trapped in region III is shown in Fig. 2 as a function of filling and storage time. The data correspond to a N_2 pressure of 1.5×10^{-6} Torr and a magnetic field of 860 G in region III. The solid curve in Fig. 2(b) corresponds to an exponential, $N(t)=N(0)\exp[-t/\tau]$, with a confinement time τ of 60 s. The maximum number of stored positrons is 3.3×10^5. Measurement of the radial distribution of the positrons (described below) shows that they do not diffuse to the electrodes but annihilate in the central region of the trap.

We have recently discovered that the positrons can form long-lived resonances with large neutral molecules, such as pump oils, which are present in small amounts in our vacuum system.[6] The positrons then annihilate in these states in times which are estimated to be of the order of 1 ns. In order to eliminate these impurities, the data in Fig. 2 were taken with a cooled baffle in the vacuum chamber near region III and with cooled walls of the vacuum chamber surrounding this region. These elements were kept at temperatures between 293 and 77 K, while the electrode structure and gas in region III were kept at room temperature. Because of gettering provided by these cold surfaces, the confinement time increased to the extent that annihilation in molecular resonances was not the dominant mechanism limiting τ. The confinement time shown in Fig. 2 is inversely proportional to N_2 pressure, and the absolute value of the lifetime agrees to within a factor of 2 with that expected[10] for free annihilation of the e^+ in collisions with N_2. Confinement of electrons[11] and positrons[12] for days has previously been achieved with significantly smaller trapping efficiency[12] in Penning traps at low gas pressures ($\sim10^{-11}$ Torr).

We have studied the time dependence of the cooling of the positrons. When the potential difference between regions II and III is set at 8.3 V, the characteristic time that the positrons remain in regions II plus III, before being trapped in region III, is 20 ms. The positrons entering region III are found to cool to energies ~1 eV in less than 0.1 s. It is likely that, in this range of energies, the positrons cool via vibrational excitation of N_2.

The subsequent cooling of the positron gas occurs at a slower rate and is either due to rotational excitation of N_2 molecules or to elastic scattering with N_2. The temperature of the positron gas in this range of energies is

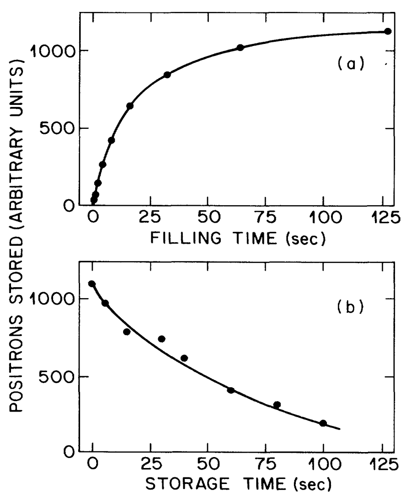

FIG. 2. (a) The total number of positrons stored as a function of filling time. (b) The number of positrons remaining as a function of storage time after a 12-s fill. The measured confinement time of 60 s is limited by direct annihilation of the positrons with N_2 in region III of Fig. 1, where the pressure is 1.5×10^{-6} Torr.

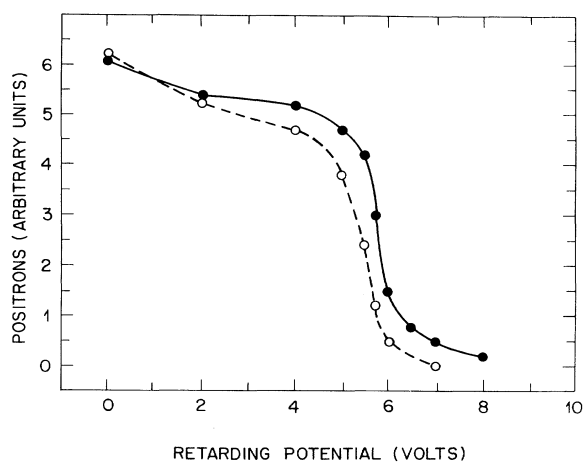

FIG. 3. Retarding potential curves of the annihilation γ-ray signal at the collector, with (open circles) and without (filled circles) a magnetic mirror field at the collector, after a storage time of 0.8 s. The magnetic field is 860 G. The shift in the curves is a measure of the perpendicular energy of the positrons in the confinement region. These data correspond to a total, average positron energy of 0.4 eV.

measured by a "magnetic beach" energy analyzer,[13] which yields the average energy $\langle E_\perp \rangle$ of the positrons perpendicular to the magnetic field. As shown in Fig. 3, the retarding potential curves of the positrons impinging on a metal collector are measured with and without an additional magnetic mirror field B_m of 1.7 kG at the collector. The resulting shift in potential ΔV of the retarding potential curves is then related to $\langle E_\perp \rangle$ by $\langle E_\perp \rangle = \Delta V(B_0/B_m)$, where B_0 is the field in region III. The distribution of positrons in the trap becomes isotropic as a result of positron-N_2 collisions on times that are short compared with the measured cooling rate; thus these data are a measure of the average, total energy of the positrons, $\langle E \rangle = \frac{3}{2} \langle E_\perp \rangle = \frac{3}{2} kT$.

Shown in Fig. 4 are data for $\langle E \rangle$ as a function of storage time for short filling times (~50–100 ms), at a magnetic field B_0 of 430 G. The characteristic time for cooling in the range of energies shown in Fig. 4 is 0.6 s. The data are plotted by subtracting the kinetic energy of 0.038 eV expected for positrons at room temperature. The fact that the data can be fitted by a single straight line confirms that the positrons are cooling to room temperature. Data taken at $B_0 = 860$ G show a similar cooling rate, but with somewhat more scatter. The origin of this noise is unclear at present.

The radial distribution of the positrons $q(r) \equiv \int dz\, n(r,z)$, where $n(r,z)$ is the positron density, is shown in Fig. 5 as measured by dumping the contents of the trap onto an arrangement of annular collectors which are biased to measure the number impinging on one collector at a time. This distribution can be fitted by a Gaussian with a $1/e$ width of 1.55 cm, which is much smaller than the 12.2-cm radius of the electrodes in the confinement region and confirms that the positrons do not diffuse to the walls.

In order to arrive at the density of the positron gas, we must also know the extent of the charge cloud along the magnetic field. The positron density $n(r,z)$, as a function of z and radius r, was calculated[14] from the Gaussian fit to $q(r)$, using Poisson's equation and the electrostatic potential produced by the electrode structure, assuming the positron gas is at room temperature. We find that the density on the magnetic axis falls to $1/e$ of its peak value at $\Delta z \cong 1.2$ cm. The maximum positron density n is found to be 2.0×10^4 cm^{-3} for the case where 3.3×10^5 positrons are stored.

The local value of the Debye length λ_D at z_0 is shown in Fig. 5, where $\lambda_D \equiv [kT/4\pi n e^2]^{1/2}$. Using the local value of n at the center of the charge cloud, we find $\lambda_D = 0.83$ cm. The fact that λ_D is not comparable to the size of the system indicates that we have entered the regime where many-body effects and classical plasma behavior are important. The two other criteria for plasma behavior are easily fulfilled. In particular, the number of particles in a Debye sphere is much larger than 1 (i.e., $n\lambda_D^3 \sim 10^4$), and the plasma frequency ω_p is much greater than the collision frequency (i.e., $\omega_p \tau_{e^+N} \sim 10^4$, where τ_{e^+N} is the collision time of the positrons with nitrogen molecules).

We expect to achieve $\sim 1\times10^9$ trapped positrons with confinement times of 3000 s using an 86-mCi ^{22}Na source. This will require operating region III at a lower pressure of 3×10^{-8} Torr in order to decrease the annihilation rate and increase the filling time (×50 increase). It also requires a decrease of magnetic mirroring which now exists between the source and confinement electrodes (×3), elimination of a factor of 5 loss now present as the positrons make the transitions between regions I and III, and a factor of 3 increase in source-moderator

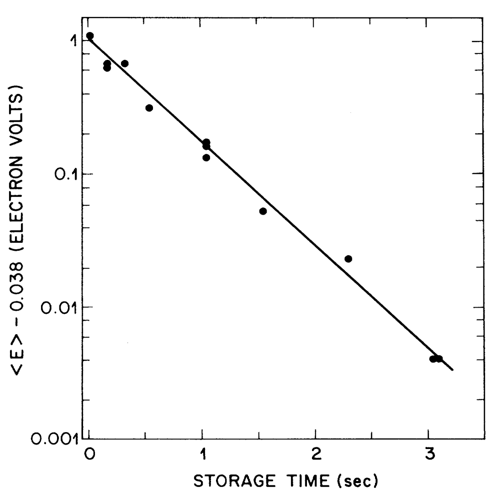

FIG. 4. The total, average energy of the positrons $\langle E \rangle$ minus their energy at room temperature as a function of storage time. The straight line corresponds to a characteristic cooling time of 0.6 s. The positrons cool to nearly room temperature in about 3 s.

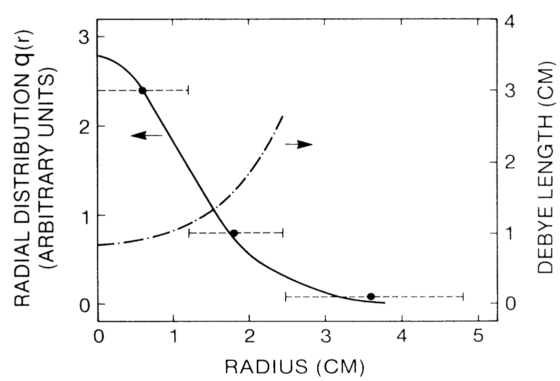

FIG. 5. The radial distribution $q(r)$ of the positrons in arbitrary units (filled circles) as measured by three collectors whose radial extent is indicated by the dashed lines. The solid curve is a Gaussian which is a best fit to the data. The resulting Debye length at $z = 0$ is shown by the dot-dashed curve, assuming the positrons are at room temperature.

efficiency.

In this Letter, we have described an experiment which has achieved the trapping and confinement of a positron gas sufficiently cold and dense to exhibit classical, plasmalike behavior. We expect that, with the addition of electrons or electron beams, such positron plasmas will be useful in studying the properties of equal-mass plasmas and as a model system to study processes relevant to astrophysics. The positron trapping scheme described here is also likely to be useful for a wide range of other scientific applications.

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